The estimation of coherence length for electron-doped superconductor $Nd_{2-x}Ce_xCuO_{4+\delta}$

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Abstract

Results of low-temperature upper critical field measurements for $Nd_{2-x}Ce_xCuO_{4+\delta}$ single crystals with various x and nonstoichiometric disorder (δ) are presented. The coherence length of pair correlation ξ and the product $k_F\xi$, where k_F is the Fermi wave vector, are estimated. It is shown that for investigated single crystals parameter $k_F\xi \cong 100$ and thus phenomenologically NdCeCuO - system is in a range of Cooper-pair-based (BCS) superconductivity.

PACS: 72.15.Gd, 74.25.Fy, 74.72.Jt

1 Introduction

In the hole-doped cuprate high-T_c superconductors the size of the pairs, as estimated from the Ginzburg-Landau coherence length ξ, is only few times the lattice spacing [1] in contrast to ordinary superconductors where the pair size greatly exceeds the lattice spacing or the average distance between carriers. In view of short coherence length of high-T_c superconductors a situation close to compact bosons with Bose-Einstein (BE) condensation at T_c is conceivable. The evolution from BCS superconductivity to BE condensation through the increase of the coupling strength between fermions was studied by Nozieres and Schmitt-Rink [2] and it was concluded that the evolution is smooth.

In [3] convenient phenomenological parameter was selected to establish the crossover from BCS superconductivity to BE condensation of composite bosons, namely, the product $k_F\xi$ of Fermi wave vector times the coherence length. Pistolesi et al. [3] argued that Cooper-pair-based superconductivity is stable against bosonization down to $k_F\xi = 2\pi$. The stabilization criterion $k_F\xi \geq 2\pi$ corresponding to the condition $\xi > \lambda_F$, with $\lambda_F = 2\pi/k_F$ being the electron wave length, should be regarded as an analog of the Ioffe-Regel criterion for transport in disordered systems [4].

It appears that for hole-doped high-T_c superconductors (series of La-, Y-, Bi- and Tl-systems) $k_F\xi \cong 10$ that are although in a BCS range but near the "instability" line $k_F\xi = 2\pi$ on the plot of T_c vs $T_F (= E_F/k)$ of Uemura et al. [5]. Our goal was to estimate a parameter $k_F\xi$ at electron-doped superconductor $Nd_{2-x}Ce_xCuO_{4+\delta}$ with various Ce concentration.

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2 Experimental results and discussion

In order to find ξ the low-temperature measurements of upper critical field B_{c2} on $Nd_{2-x}Ce_xCuO_{4+\delta}$ single crystal films with various Ce concentration and nonstoichiometric disorder δ [6] in magnetic fields up to 9T ($B \parallel c$, $J \parallel ab$) and temperature range 0.4-40 K with SQUID-magnitometer MPMS XL of Quantum Design and by dc-current method in solenoid up to 12T from "Oxford Instruments" were carried out.

In Fig.1 the dependencies of the resistivity ρ in CuO_2 - planes ($J \parallel ab$) on perpendicular magnetic field $B \parallel c$ are presented for optimally reduced films with $x = 0.14$; 0.15; 0.18; 0.20 and an example of B_{c2} determination (for x =0.15 at T = 0.4 K) is shown. As it should be obtained B_{c2} value is the higest for optimally doped sample with with $x = 0.15$.

Fig.2 demonstrates an effect of nonstoichiometric disorder on the upper critical field of optimally doped $Nd_{1.85}Ce_{0.15}CuO_{4+\delta}$ system. Results of magnetoresistance measurement are presented for three types of $Nd_{2-x}Ce_xCuO_{4+\delta}$ single crystal films [7]: as-grown samples, optimally reduced samples (optimally annealed in a vacuum at T = 780^0 C for t = 60 min; p = 10^{-2} mmHg) and non optimally reduced samples (annealed in a vacuum T = 780^0 C for t = 40 min; p = 10^{-2} mmHg). The film thikness was 1200 - 2000 Å .

Using the relation between the coherence length and the upper critical field $2\pi B_{c2}\xi^2 = \Phi_0$ where the elementary flux quantum $\Phi_0 = \pi c\hbar/e$, the values of ξ for all samples were estimated. The data for normal state in-plane resistivity and Hall coefficient [6] were turned to account for determination of parameter $k_F\ell$, mean free path ℓ and $k_F = (2\pi n_s)^{1/2}$, n_s being the surface electron density. All the obtained parameters along with the $k_F\xi$ values are presented in Table 1 for optimally reduced samples with different Ce concentration and in Table 2 for samples with $x = 0.15$ and different nonstoichiometric disorder. It is known [8] that for "dirty" ($\ell < \xi$) s-wave superconductor

$$B_{c2}(T=0) = \frac{1}{2\gamma} \cdot \frac{\Phi_0}{\hbar D} \cdot kT_c \tag{1}$$

where constant $\gamma \cong 1.78$, $D = v_F\ell/2 = \frac{\hbar}{2m} k_F\ell$ is the diffusion coefficient, v_F is Fermi velocity.

Then

$$\xi = \sqrt{\xi_0 \ell}, \tag{2}$$

where $\xi_0 \cong \frac{\hbar v_F}{kT_c}$ is the coherence length in pure superconductor. From (1) and (2) we have $B_{c2} \sim (k_F\ell)^{-1}$ and $\xi \sim \sqrt{k_F\ell}$, thus B_{c2} should *increase* and ξ should *decrease* with increase of $(k_F\ell)^{-1}$ as a degree of disorder.

As it is seen from Table 2 for $Nd_{1.85}Ce_{0.15}CuO_{4+\delta}$ the upper critical field quickly *decreases* and the coherence length *increases* with increasing of degree of disorder (parameter $(k_F\ell)^{-1}$) in contradiction with standard results for s-wave superconductor. Such an unusual behavior of B_{c2} and ξ with variation of disorder may be an evidence of d-wave symmetry of superconducting order parameter for $Nd_{1.85}Ce_{0.15}CuO_{4+\delta}$. It is in accordance with the theoretical considerations of Yin and Maki [9] for d-wave superconductors as with our results for a slope of upper critical field in vicinity of T_c in this electron doped system [10].

In Fig.3 a log-log plot of T_c versus Fermi temperature $T_F = \varepsilon_F/k$ (so named "Uemura plot" [5]) for different superconductors is presented and the points for $Nd_{2-x}Ce_xCuO_{4+\delta}$ system received by us are also shown. The lines with constant $k_F\xi$ values ($k_F\xi = 2\pi$ and $k_F\xi = 10^n$, $n = 1 \div 5$) are superimposed on the plot according to [3]. It may be seen that parameter $k_F\xi \cong 100$ for different samples of single crystals $Nd_{2-x}Ce_xCuO_{4+\delta}$ with various Ce concentration and nonstoichiometric disorder. Thus this electron doped system is even more deep in the region of BCS-coupling than hole-doped cuprate systems. The value of $k_F\xi$

is minimal for optimally doped system ($k_F\xi = 70 \div 80$ and nearly independent on a degree of disorder) and increases for overdoped ($x = 0.18$ and 0.20) samples.

3 Conclusions

Thus, from a values of upper critical field we estimate the coherence length in $Nd_{2-x}Ce_xCuO_{4+\delta}$ system with various x and δ. Then, using the universal (independent of the details of the interaction potential) phenomenological parameter $k_F\xi$ [3], we illustrate that investigated electron doped cuprate NdCeCuO system doesn't cross the instability line of BCS superconductivity $k_F\xi = 2\pi$ even for optimally doped and optimally reduced samples.

We are grateful to V.N.Neverov for experimental support. This work was done within RAS Programm (project N 01.2.006.13394).

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Table 1

Table 1: The data for $Nd_{2-x}Ce_xCuO_4$ optimally reduced films.

Samples	T_c,K	B_{c2}, T	$k_F\ell$	ξ,Å	$k_F\xi$
x=0.14	11	2.9	2.7	106.5	-
x=0.15	21	6.1	51.6	73.5	74.2
x=0.18	6	0.76	44.4	207.7	118.4
x=0.20	<1.3	0.4	14.6	273.3	166.7

Table 2

Table 2: The data for $Nd_{1.85}Ce_{0.15}CuO_{4+\delta}$ films with different nonstoichiometric disorder.

Samples	B_{c2}, T	$k_F\ell$	ℓ,Å	ξ,Å	$k_F\xi$
Optimally reduced	6.1	51.6	51.3	73.5	74.2
Non optimally reduced	4.8	9.1	12.5	82.3	68.3
As grown	1.3	8.6	13.4	158.7	80.9

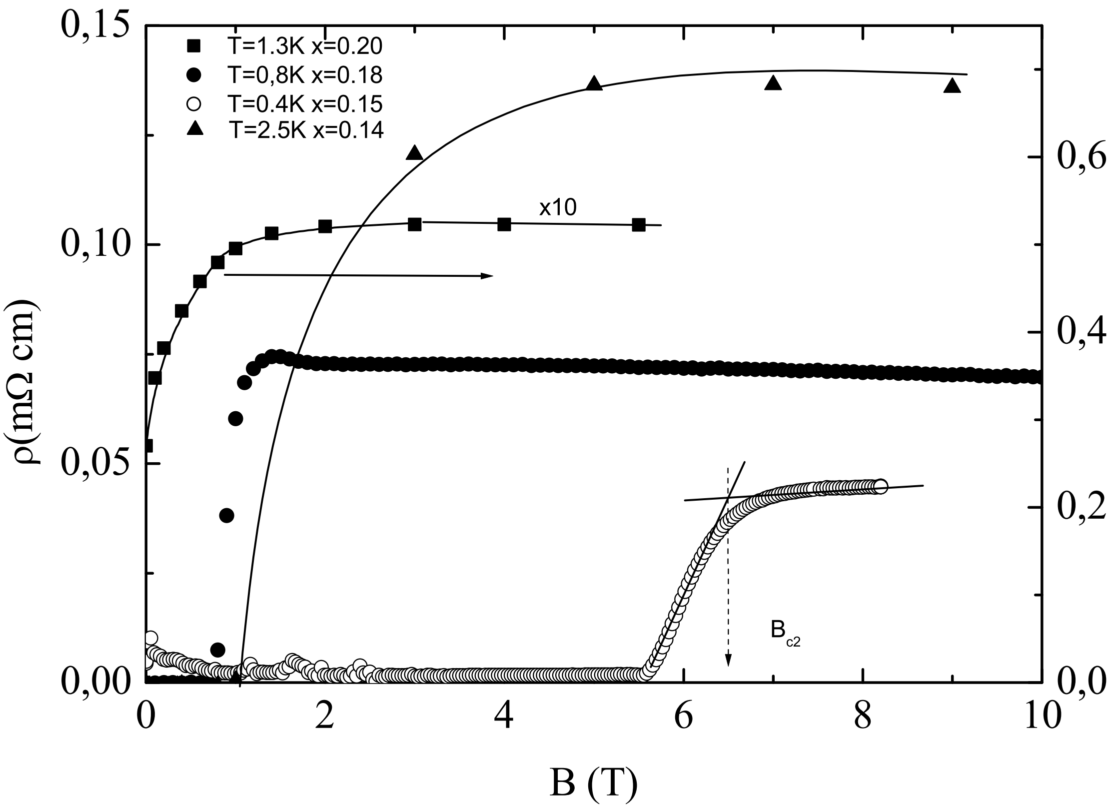

Figure 1: Resistivity at CuO_2-planes ($J \parallel ab$) vs magnetic field ($B \parallel c$) for samples $Nd_{2-x}Ce_xCuO_4$ with different Ce concentration at low temperatures. The lines are guides to the eye.

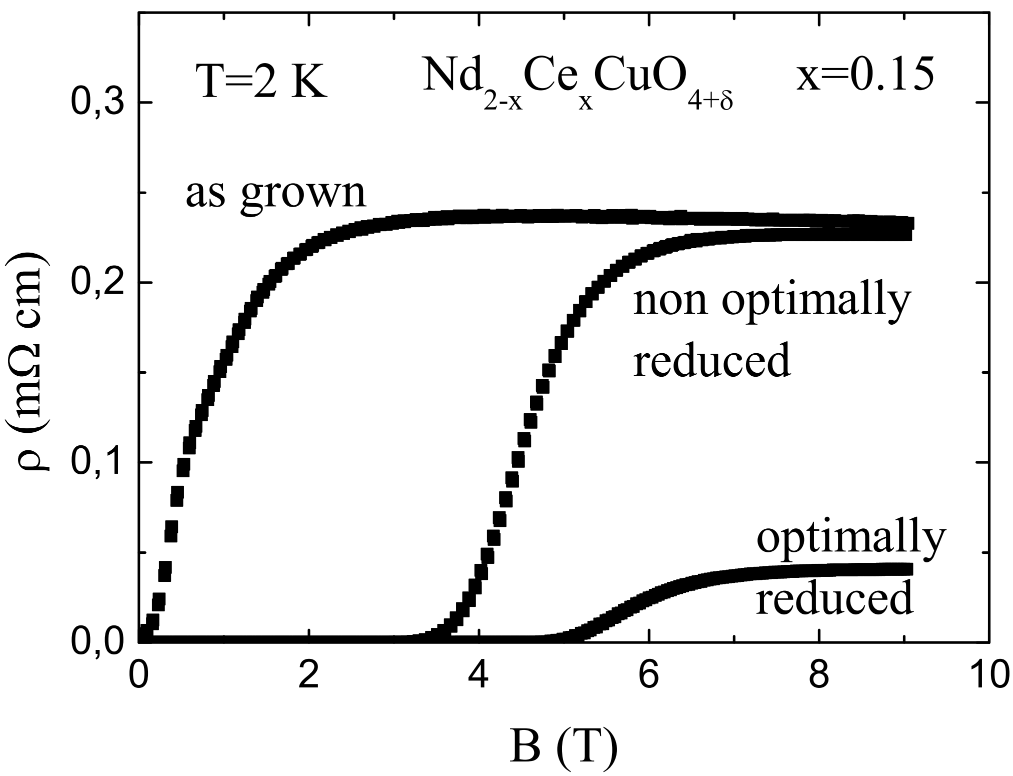

Figure 2: Resistivity at CuO_2-planes ($J \parallel ab$) vs magnetic field ($B \parallel c$) for samples $Nd_{1.85}Ce_{0.15}CuO_4$ with different nonstoichiometric disorder at $T = 2$ K.

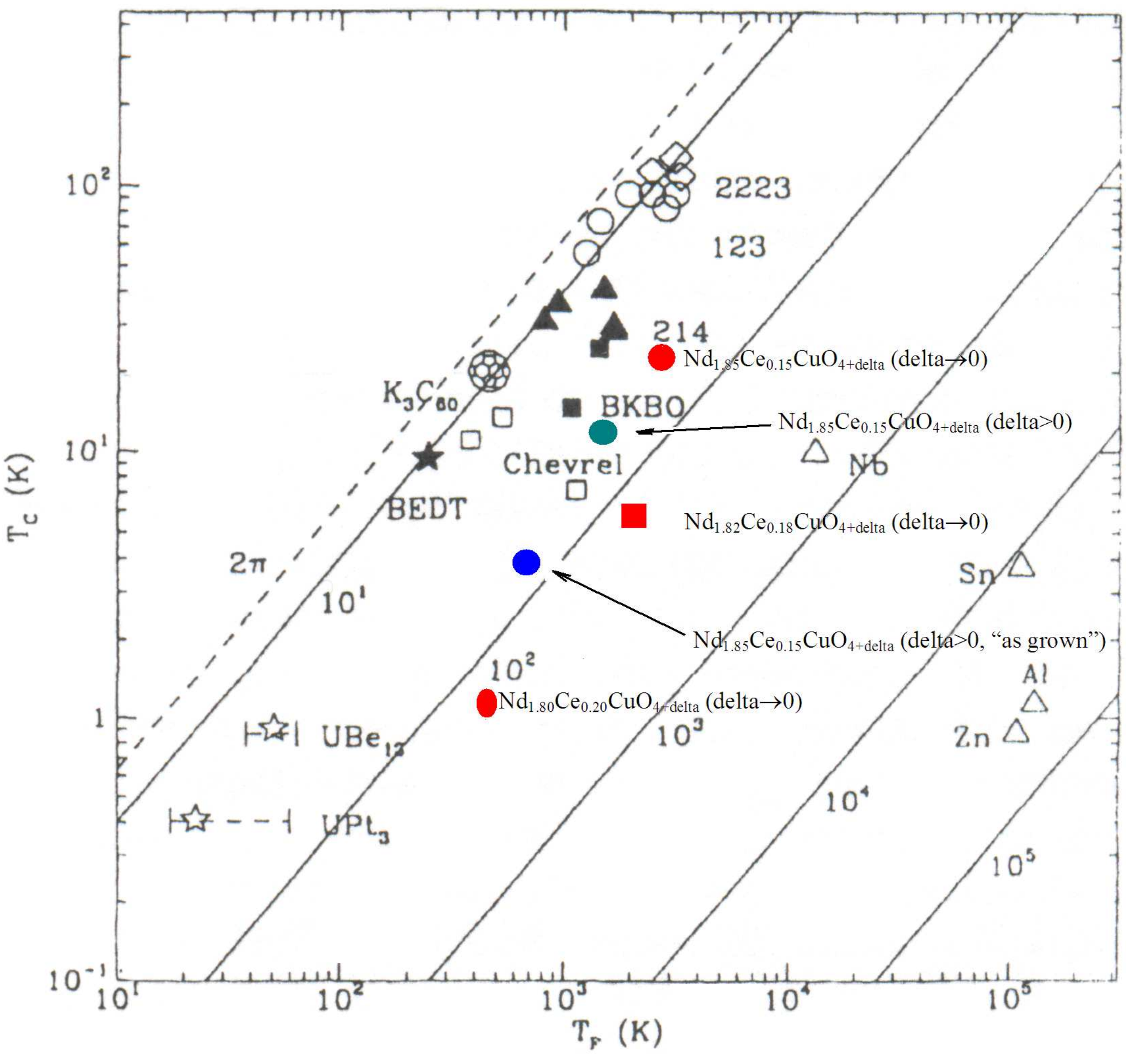

Figure 3: "Uemura plot" [5] with constant $k_F\xi$ lines [3] and with our points for $Nd_{2-x}Ce_xCuO_{4+\delta}$ system.